

## AFSPC Astrodynamic Standards – The Way of the Future

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### **Executive Summary**

Numerous astrodynamic algorithms have been independently re-developed by Air Force Space Command (AFSPC) over the past twenty-five years to fulfill its Space Control mission. The result was a proliferation of redundant algorithms that were all maintained separately at increased cost and risk to AFSPC.

In 1995, Astrodynamic Standard algorithms were developed in FORTRAN 77 by AFSPC to emulate the operational algorithms used by the AF Space Control Center (AFSCC) at Cheyenne Mountain Air Force Station and reduce the proliferation of redundant algorithms. Hundreds of copies of the AFSPC Astrodynamic Standards have been released to the user community and the code has been integrated successfully.

Today, requests for standards come from developers who want a callable astrodynamic library function that will feed a graphics application and a database. They also want modular code that can function on different platforms across local or worldwide networks. While the standards had successfully contributed to reduce software development and maintenance costs, their current form was inadequate to easily meet modern software development requirements.

This paper describes AFSPC's current effort to upgrade the AFSPC Astrodynamic Standards to meet modern developer needs. AFSPC is also planning to establish astrodynamic standard software, as callable library functions, within the AFSCC. AFSPC's goal is to provide a "Gold Standard" suite of astrodynamic standard software that will ensure accuracy, minimize risk and cost, and provide users with rapid implementation of new improvements.

### **Historic Motivation to Develop Standards**

Numerous astrodynamic tools and algorithms have been developed by Air Force Space Command (AFSPC) to fulfill its Space Surveillance mission. These algorithms were tested, reliable, and compatible with the data gathered and distributed for use by the Space Surveillance Network (SSN). However, as network users updated old systems and brought new ones on line, site-specific software was often developed. Many times it fell on the site contractor to create or obtain software that would process and produce SSN data. Since it was often difficult to obtain the desired software from AFSPC, contractors would develop a solution. The result was a proliferation of redundant algorithms that were all maintained separately at increased cost and risk to AFSPC.

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<b>14. ABSTRACT</b> Numerous astrodynamic algorithms have been independently re-developed by Air Force Space Command (AFSPC) over the past twenty-five years to fulfill its Space Control mission. The result was a proliferation of redundant algorithms that were all maintained separately at increased cost and risk to AFSPC.				
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A viable solution was to release existing software to qualified users. The problem was that SSN-compatible software included extremely large and complex bodies of code written under a computing paradigm that assumed full time dedicated software maintainers, minimum use of memory, and full optimization of execution time. It was born of an era when thousands of punch cards were meticulously prepared and stored in large boxes, and hardware maintenance costs often exceeded those of software maintenance. Developers prior to 1980 could not foresee the advent of analysis tools, high speed computing on cheap and reliable PCs, distributed applications, the internet, powerful graphics applications, advanced developer environments, modular code and object-oriented languages that emphasize reuse of code, flexibility, platform independence, and reduced software maintenance budgets. Today, a desktop PC handles in seconds or minutes a job that took a mainframe hours to run. Job runs that humbled the mighty Cray supercomputers of a decade ago are routine on the latest desktops.

### **AFSPC Role in Astrodynamic Standards**

In 1991 USSPACECOM/J3 tasked HQ AFSPC/DO to be the technical lead for astrodynamic standards. Despite the monolithic and inflexible nature of the code used on the main frame computers, the physics of the astrodynamic models were, and still are, comparable to anything available today, so during the early 90's AFSPC undertook the task of extracting desired algorithms from the larger programs in SPADOC and officially recognized them as the AFSPC Astrodynamic Standards. They were created to provide tested, trusted, and centrally maintained SSN compatible code to ensure interoperability, and to avoid spending money reinventing and separately maintaining code whose capability was already available. These algorithms are currently released as no cost GOTS ( Government off the shelf ) products to qualified DOD contractors and Government users for installation in programs that use or provide data to the SSN.

AFSPCI60-102, "Space Surveillance Astrodynamic Standards", sets the minimum standards required for interoperability within the space surveillance mission area. Although this instruction was established in 1996, HQ AFSPC/DOY later determined that it was not being enforced. As a result, HQ AFSPC/DOY is currently updating this instruction and is seeking Command approval for specifying the use of AFSPC astrodynamic standards in all new or upgraded AFSPC systems that use satellite trajectories and related data from the Air Force Space Control Center (AFSCC).

### **AFSPC Reasons for Requiring Use of Astrodynamic Standards**

There are basically three reasons for the Command's advocacy of astrodynamic standards: (1) ensuring the accuracy of astrodynamic algorithms used throughout the Command, (2) minimizing the risk and cost of providing required algorithms for AFSPC operational units, and (3) maintaining the ability to rapidly distribute improved astrodynamic algorithms.

## 1) Accuracy:

The accuracy of an astrodynamic algorithm is primarily a function of its underlying physics model and the accuracy and compatibility of the data it uses. It is easy to understand that the "better" the underlying physics model or the more accurate the data, the more accurate the algorithm's calculation. However, it is not as intuitively obvious that the prediction model must also be compatible with those models generating the orbital data that it uses as input.

If the data products (satellite orbit element sets or vectors) produced by the AFSCC orbit fit algorithm are used by a customer with a compatible algorithm, they will make the "most accurate" calculation possible. However if this AFSCC satellite orbit vector is used by a customer with a non-compatible algorithm, they will get a "less accurate" answer.

Figure 1. gives an example of an actual operational incompatibility when predicting the location of a satellite. A user wanted to upgrade their WGS-72 geopotential model to the more accurate WGS-84. However, they were still receiving their data input in the

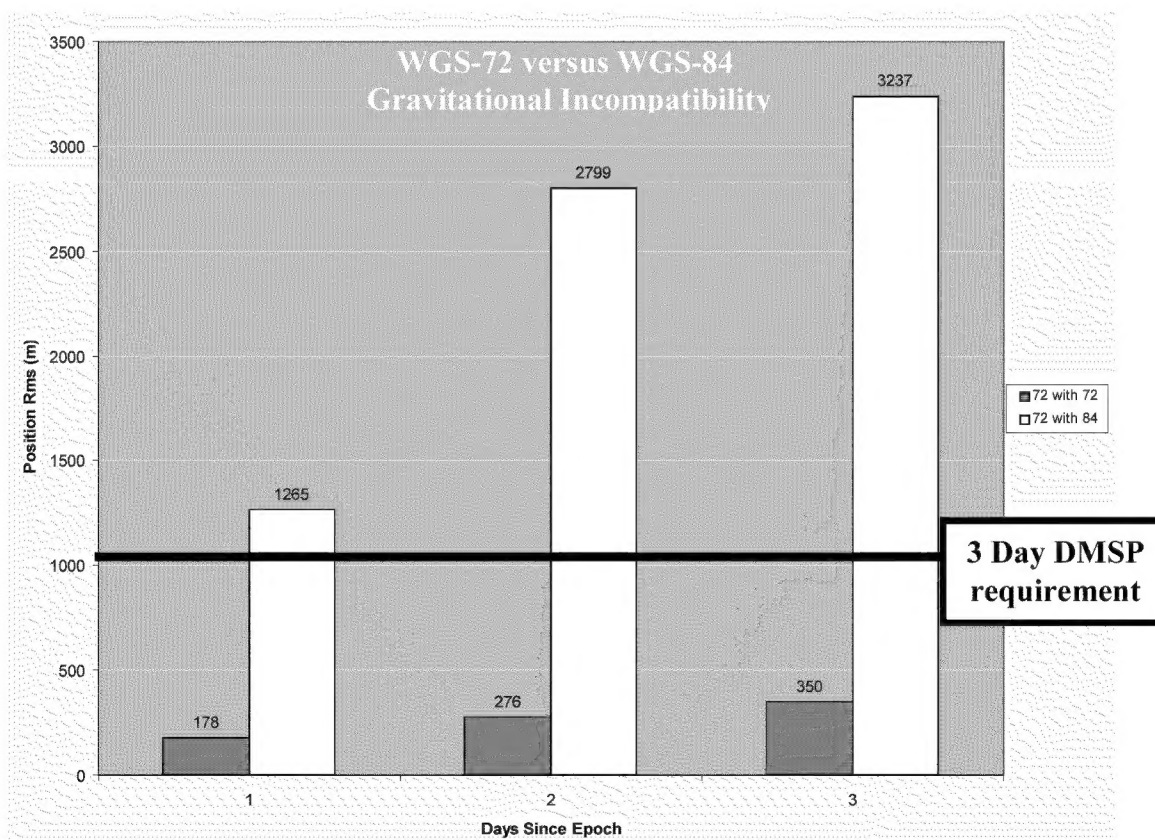


Figure 1. Predictions with AFSCC vectors using WGS-72 versus WGS-84

form of WGS-72 produced vectors from the AFSCC. They had an accuracy requirement for DMSP satellites that a prediction would still be within one kilometer after three days, which they met with their old WGS-72 model (as shown in dark blue in the table above). However, if they had decided to upgrade to the incompatible, "but more accurate," geopotential model they would have failed to meet this requirement even after one day, let alone three (as shown in light blue in the table above).

To ensure compatibility the customer's astrodynamic algorithm needs to be the same algorithm that was used in the AFSCC to generate the input orbital data.

## **2) Minimize Risk and Cost**

There are hundreds of customers within AFSPC, using AFSCC data products to make similar astrodynamic calculations. Building new algorithms for every operational unit is needlessly expensive and only adds risk to mission success because the resulting algorithm may be incorrect. The Verification, Validation and Accreditation (VV&A) needed to ensure correctness is also expensive and time consuming. However, the cost doesn't end with an algorithm's initial development. AFSPC must continue to pay for sustainment of all these systems. Individually maintaining multiple stovepipes adds unnecessary risk and cost.

## **3) Rapid Updates**

AFSPC would like to be able to make improvements to astrodynamic algorithms and distribute them rapidly throughout AFSPC. This requires that both the algorithms (models) and the computer software are standardized...astrodynamic standard software, if you will.

In the past AFSPC has been constrained in making improvements to the AFSCC algorithms because their customers could not easily make the same changes to their operational code. If the AFSCC develops an improved astrodynamic algorithm but the other AFSPC operational units don't adopt it, that SCC "improvement" would only cause incompatibilities between the SCC data products and the customer's astrodynamic algorithms. Therefore, in many cases new improvements to the SCC algorithms could not be effectively implemented because of the subsequent cost to the operational units using their products (e.g. there are users today that are still using the 1960's orbit propagator called SGP).

The technology exists today to build "Gold Standard" astrodynamic algorithms ...astrodynamic standard software...that would reside in the AFSCC. Improvements could be made to the AFSCC software and that same software could then be simultaneously released to all customers within AFSPC. If the customer has built their application to interface with this modular software, then it would just be a simple plug-and-play update for them. This would be similar to how we now get our new version releases of Microsoft Word for example, the customer does not have to build new code or compile new code in order to implement the improved version. However, until all of



the legacy users are updated to the modular code, AFSPC will continue to supply the products needed to meet their mission requirements.

### **Difficulties with Current Standards Implementation**

Hundreds of copies of the Astrodynamic Standards have been released to the user community and the code has been integrated successfully. However, the increasing cry has been for modular pieces of code that are called like a simple function and return an answer. Developers want the code written in the language of their choice or as a callable function to support integration in larger applications that further process the data. The current releasable standards are written in FORTRAN 77 and have an inflexible DOS-type user interface, which takes input and writes an output file which is not changeable by the user. As a result, developers are motivated to request the source code, and thereby incur the risk of corrupting the tested standard code and forcing additional software maintenance. The associated costs are passed on to AFSPC, and costly hybrid algorithms proliferate. The problem that precipitated creating standards was not completely solved. While the standards have successfully contributed to reduce software development and maintenance costs, their current form is inadequate to easily meet modern software development requirements.

### **Migrating Astrodynamic Software into the New Century**

Requests for standards today come from developers who want a callable astrodynamic library function that will feed a graphics application and a database. They create their own user interfaces and format their own output to feed graphical displays and various databases. They want modular code that can function on different platforms across local or worldwide networks.

AFSPC has started a phased effort to modernize the astrodynamic standards (see Appendix A for a description of these standards) to meet modern developer needs. The following steps are involved:

- 1) Untangle and modularize the F77 code while migrating to FORTRAN 95, which represents minimal risk within funding constraints. FORTRAN 95 is:
  - a) Accessible to users, directly or through a C wrapper. This includes legacy ADA, C, and F77 users as well as developers using object-oriented languages.
  - b) Supported by modern software analysis tools and developer environments that simplify program maintenance and reduce associated costs.
  - c) Lends itself to eventual migration to C/C++ or JAVA.
- 2) Remove unnecessary interfaces and allow for developers to use their own designs for input and output (I/O). While a simple driver program would accompany each algorithm and would provide simple input and output, developers are free to replace it with their own.
- 3) Provide the algorithm as a callable library, shared object, or Dynamic Linked Library (DLL). Once the user adds the compiled library to their code and links it to his/her program, the algorithm is accessed by a single function call.
- 4) Migrate the code if necessary to C, which is most flexible for inter-language calling.

- 5) Move toward platform independent executable libraries as resources permit.

### **Status of the FORTRAN 95 Software as of 1 March, 2001**

- 1) The Simplified General Perturbations 4 (SGP4) propagator algorithm has been delivered and has undergone extensive code review and testing. It has been compiled into a static library on the (SGI) UNIX platform and a DLL on the Intel PC. Release of Version 5.0 will take place in March.
- 2) The Special Perturbations (SPEPH) propagator algorithm has been delivered and has undergone extensive code review and testing. Numerical tests so far are successful and additional driver software is being written to develop the DLL and the customer sample application.
- 3) The Computation of Miss Between Orbits (COMBO) algorithm has been delivered and has undergone extensive code review and testing. Numerical tests so far are successful and additional driver software is being written to develop the DLL and the customer sample application.
- 4) The Look Angles Module (LAMOD) algorithm, used for calculating sensor site look angles to acquire passing satellites, has been delivered and has undergone extensive code review and testing. Numerical tests so far are successful and additional driver software is being written to develop the DLL and the customer sample application.
- 5) The Report/Observation Association (ROTAS) algorithm has been delivered and has undergone extensive code review and testing. Numerical tests so far are successful and additional driver software is being written to develop the DLL and the customer sample application.
- 6) Additional algorithms, including SGP4/SP DC, IOMOD, AOF, FOV, and SEQDC, are currently being developed.

### **Concerns**

However some concerns have been expressed concerning astrodynamic standards. One concern is that an instruction or regulation doesn't mean much if it can't be enforced. This is the reason AFSPC/DOY is seeking Command approval for specifying the use of AFSPC astrodynamic standards. One way to create an enforceable set of standards is to incorporate them into the Operational Requirements Document (ORD) for new or upgraded systems. This is a method that AFSPC/DOY advocates and is trying to determine the most appropriate method of incorporation.

Another concern is that if restrictive performance and interoperability standards get set by the command, the customer will be unable to exploit numerous commercial space operations software applications that may be perfectly suitable for the intended mission. There are two facets to this concern, customers with "unique" requirements and those whose needs are met by the current algorithms but who would also like to be able to "exploit" the graphical capabilities of COTS products.

For the case when the standards do not meet users' requirements, the proposed AFSPC Instruction does not prohibit customers from developing "specialized" algorithms. AFSPCI60-102 allows the DO and DR Command Leads to submit a request for a waiver from using the astrodynamic standards. This request is then reviewed by AFSPC/DO to determine if this is the best and most cost effective solution for AFSPC. If a waiver is granted, the AFSPC operational user incurs responsibility for ensuring the "specialized" algorithm is properly VV&Aed and is compatible with the AFSCC products that it must use.

For the case when the standards do meet users' requirements, AFSPCI 60-102 will direct their usage; thus ensuring accuracy, minimizing risk and cost and providing for rapid improvements. Additionally, the future AFSPC COTS plug-in module" astrodynamic standards will satisfy the customers within AFSPC who would like to exploit the many COTS visualization products available and yet be assured they get accurate answers with AFSCC data products. This not only ensures that the customer obtains the most accurate answers that they require, but also this minimizes risk and cost and provides the ability to rapidly incorporate improved astrodynamic algorithms.

## **The Way Ahead**

As specified by the Integrated Space Command and Control (ISC2) contract, Lockheed Martin and their ISC2 teammates will take responsibility for maintaining the AFSPC Astrodynamic Standards Software. Lockheed Martin will assume responsibility from the Space Warfare Center/Analysis and Engineering Division (SWC/AE) for maintenance and distribution of all the current and to be developed standards, as they become available. Also specified by the NORAD/USPACECOM Warfighting Support System (N/UWSS) Technical Architecture, Lockheed Martin is required to implement the AFSPC Astrodynamic Standard Software in new products for ISC2.

To facilitate this transition, AFSPC/DOY and SWC/AE are working with Lockheed Martin to provide, assist with implementation of, and perform verification and validation (V&V) of the new software as it is being developed. This is a big step towards achieving AFSPC's goal to provide a "Gold Standard" suite of astrodynamic standard software that will ensure the most accurate answer for users of AFSCC data, minimize risk and cost, and provide users with rapid implementation of new improvements.



## **APPENDIX A - AFSPC Astrodynamic Standard Software**

SWC/AES maintains, for AFSPC, the following standardized Astrodynamic Software. The AFSPC Astrodynamic Standards are currently available as stand-alone FORTRAN 77 executable modules portable to UNIX, PC, or VMS platforms. An effort is currently underway to modularize these standards in FORTRAN 95 and C.

### **ORBITAL APPLICATIONS**

- Look Angle Generation (LAMOD)
- Computation of Miss Between Orbits (COMBO)
- Overfly (AOF)
- Field of View (FOV - Laser Clearinghouse)
- New Foreign Launch (NFL - initial launch parameters)
- Decay Prediction (SALTLIFE)

### **EPHEMERIS GENERATION**

- SGP4
- SALT
- SP

### **ORBITAL CORRECTION**

- SGP4DC
- SALTDC
- SPDC
- Sequential DC

### **OBSERVATION ASSOCIATION**

- ROTAS

### **INITIAL ORBIT GENERATION**

- IOMOD

### **ELEMENT CONVERSION**

- Converts element sets, vectors or observations to element sets or vectors of another theory type (SGP4, SALT or SP)

## **AFSPC ASTRODYNAMIC STANDARDS**

- 1) SGP4 - (Simplified General Perturbations #4)** - Is an analytic method of generating ephemerides for satellites in earth-centered orbits.
- 2) SGP4DC - (SGP4 Differential Correction)** - Performs a least squares differential correction of orbital elements using tracking data and the SGP4 propagator.
- 3) SP - (Special Perturbations)** - Is an algorithm, which uses numerical integration to generate ephemerides for satellites in earth-centered orbits.
- 4) SPDC - (SP Differential Correction)** - Performs a least squares differential correction of orbital elements using tracking data and the SP propagator.
- 5) SALT - (Semi-Analytic Liu Theory)** - Is a semi-analytic method of providing ephemerides and orbital lifetime analysis for satellites in earth-centered orbits.
- 6) SALTDC - (SALT Differential Correction)** - Performs a least squares differential correction of orbital elements using tracking data and the SALT propagator.
- 7) LAMOD** - Computes sensor (ground based or space based) viewing opportunities (so-called "look angles") for earth centered satellites. LAMOD uses any one of three ephemeris generation theories: SGP4, SALT, and SP.
- 8) IOMOD** - Computes an initial set of orbital elements from three observations.
- 9) AOF - (Area Overflight)** – AOF computes when overhead satellites can see a particular location on the earth (may be either a point, circle, or box). AOF uses any one of three ephemeris generation theories: SGP4, SALT, and SP.
- 10) FOV - (Field-of-View)** – FOV determines times in which orbiting satellites fly through a ground based observer's conical field of view. The field of view can be defined by a constant azimuth and elevation, a constant right ascension and declination, or as a line-of-sight to another orbiting satellite. FOV uses any one of three ephemeris generation theories: SGP4, SALT, and SP.
- 11) COMBO - (Computation of Miss Between Orbits)** - Computes close approaches between satellites using any one of three ephemeris generation theories: SGP4, SALT, and SP.
- 12) ROTAS - (Report/Observation Association)** - Associates observations against satellite element sets.
- 13) SEQDC** - Sequential Differential Correction performs a series of least-squares differential corrections (DC). These differential corrections are computed in a sequential mode, which uses one or more observations or tracks while retrieving former covariance

information from a prior DC. The user may select any of the Astrodynamics Standard ephemeris generation theories SGP4, SALT, or SP.

**14) GELCON** – Converts element sets or vectors of one of three theories (SGP4, SALT, or SP) to element sets or vectors of a selected theory (SGP4, SALT, or SP).